frontiers in Marine Science

HYPOTHESIS AND THEORY
published: 27 December 2016
doi: 10.3389/fmars.2016.00273

Where Does River Runoff Matter for Coastal Marine Conservation?

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OPEN ACCESS

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Specialty section:
This article was submitted to Marine Affairs and Policy, a section of the journal Frontiers in Marine Science

Received: *17 July 2016*
Accepted: *09 December 2016*
Published: *27 December 2016*

Citation:
Fredston-Hermann A, Brown CJ, Albert S, Klein CJ, Mangubhai S, Nelson JL, Teneva L, Wenger A, Gaines SD and Halpern BS (2016) Where Does River Runoff Matter for Coastal Marine Conservation? Front. Mar. Sci. 3:273. doi: 10.3389/fmars.2016.00273

Excess sediment and nutrient runoff from land-based human activities are considered serious threats to coastal and marine ecosystems by most conservation practitioners, resource managers, fishers, and other "downstream" resource users. Deleterious consequences of coastal runoff, including eutrophication and hypoxia, have been observed worldwide. Literature on integrated coastal management offers numerous methods to address land-based activities that generate runoff, but many of these approaches are time- and resource-intensive. Often, high-level conservation managers have few tools to aid in decisions about whether land-based threats that generate runoff are of sufficient concern to warrant further investment in planning and management interventions. To address this decision-making process, we present a decision tree that uses geophysical and ecological characteristics to sort any marine coastal ecosystem into a category of high, moderate, low, or minimal risk from the land-based threats of nutrient and sediment runoff. By identifying situations where runoff could influence biodiversity or ecosystem services, the decision tree assists managers in making informed, and standardized decisions about when and where to invest further efforts in integrated land-sea planning. We ground-truth the decision tree by evaluating it in five very different regions and conclude the tree classifies regions similarly to the existing literature that is available, but based on less information. Recognizing that the decision tree only encompasses environmental variables, we also discuss approaches for interpreting the decision tree's outputs in local social and economic contexts. The tree provides a tool for conservation managers to decide whether the scope of their work should include land-sea planning.

Keywords: conservation planning, coral reefs, eutrophication, integrated coastal management, land-sea

INTRODUCTION

Coastal and marine ecosystems experience anthropogenic pressures at scales from local (e.g., fishing, coastal development) to global (e.g., warming, acidification, rising seas), many of which originate beyond the coastal oceans (Halpern et al., 2008b, 2012). Riverine transport is the primary mechanism for direct impacts of terrestrial human activities on the nearshore marine environment (Alongi, 1998; Rabouille et al., 2001; Halpern et al., 2015). The negative effects of excess nutrients and sediments transported by rivers to coastal oceans have been well-described worldwide (Smith et al., 1999; Rabalais et al., 2002; Fabricius, 2005) and are perceived as a major concern by conservation practitioners and resource managers. However, practitioners are often faced with coastal management and planning decisions without a systematic process to assess the relative importance of land-based impacts. Gathering sufficient data for a single region to quantitatively determine the ecological, economic, and social impacts of anthropogenic runoff is extremely time- and resource-intensive, and beyond the capacity of most coastal marine managers worldwide. Coarse, large-scale assessments of runoff risk can inform global priorities for conservation (Halpern et al., 2009), but provide little aid to local managers operating at the watershed or regional scale. This study seeks to provide a rapid tool for managers in data-poor coastal marine regions to determine whether costly land-sea planning is necessary, based on the threat of anthropogenic nutrient and sediment loading.

Sediments and nutrients typically co-occur in freshwater runoff, even though the dynamics and impacts of those two pressures are not identical. Export of sediments and nutrients into coastal zones may originate from numerous point sources—wastewater effluent, storm water outfalls, runoff from waste storage—and nonpoint sources—atmospheric deposition, deforestation, land conversion, and runoff from agriculture or ranching (Carpenter et al., 1998; Howarth et al., 2012; Kroon et al., 2012). Nutrient additions to coastal and marine ecosystems can lead to increased phytoplankton abundance, including harmful algal blooms (Cloern, 2001), and can alter marine vegetative communities by lending a competitive advantage to some species of macroalgae (Lapointe et al., 2004b). Harmful algal blooms may impact benthic habitats, like corals, to varying degrees, and may result in large-scale mortality and prevalence of coral disease (Foster et al., 2011). In extreme cases, the bacterial decomposition of these phytoplankton blooms depletes dissolved oxygen levels to such an extent that most marine life cannot survive, creating anoxic "dead zones" in the coastal oceans (Diaz and Rosenberg, 2008). Both nutrient and sediment loading can also lead to increased turbidity and reduced light availability, which in turn negatively impact biogenic species such as corals (Cloern, 2001). Sediment may also physically smother sensitive habitats and impair larval development of fishes (Fabricius, 2005; Wenger et al., 2014). Although other human activities clearly impact the coastal and marine environment, such as dredging, extraction, and coastal development (Halpern et al., 2008b, 2009), this study focuses exclusively on runoff because its effects on species and habitats are uniquely challenging to observe and quantify, its management is particularly complex, and it is widely perceived as a global threat to data-poor regions. In the land-sea context, we define data poor regions as locations that do not have sufficient historical data and technical capacity to develop complete process descriptions linking activities on land to their impacts on ocean ecosystems (Pikitch et al., 2004).

Despite our understanding of runoff processes and ecosystem effects, and a robust literature on land-sea conservation planning and integrated coastal management (Cicin-Sain and Belfiore, 2005; Stoms et al., 2005; Klein et al., 2010; Álvarez-Romero et al., 2011), it remains difficult to determine whether land-sea planning should be included within the scope of a given marine conservation project or management initiative (although see Tallis et al., 2008). Pressures on marine ecosystems that originate on land are uniquely difficult to address, because they require cooperation across agencies, industries, and communities that often do not work together or even communicate (Álvarez-Romero et al., 2015). Integrating land-sea connections into natural resource management is complex and time-intensive (Brodie et al., 2012; Makino et al., 2013) and may not be feasible in all settings. Additionally, in many data-poor regions, determining whether to even consider land-sea connections in planning is challenging and uncertain. Managers need a rapid method to determine and communicate whether land-based impacts in their region should be included within the scope of management or conservation, and therefore warrant further investment in data collection, analysis, and management interventions.

To address the gap between the land-sea planning literature and resource-limited regions, we developed a decision tree to help natural resource or conservation managers decide whether land-based human activities need to be included within the scope of their endeavors (**Figure 1**). Although this decision tree can be applied anywhere, it is designed with data-poor contexts in mind. In regions where sediment and nutrient runoff from land-based activities are not a major threat to coastal and marine environments (Halpern et al., 2009), this decision tree can provide a logical basis for investing in other management actions without wasting resources on land-sea planning. Conversely, this decision tree may highlight priority regions where managers should allocate their limited resources to land-sea planning due to the high risk posed by sediment and nutrient runoff. We envisage that regional managers and other high-level conservation practitioners could use this tool to evaluate data-poor or unfamiliar regions, to reinforce or reevaluate their degree of concern about runoff, and to standardize and communicate their interpretations of runoff impacts among regions. We ground-truthed the decision tree with five test regions using published literature and the regional expertise of authors, finding marked variability in the importance of land-based pressures.

METHODS

We used a three-step process to anticipate where human-caused nutrient and sediment loading will likely affect nearshore marine ecosystems. First, we drew on hydrology and coastal

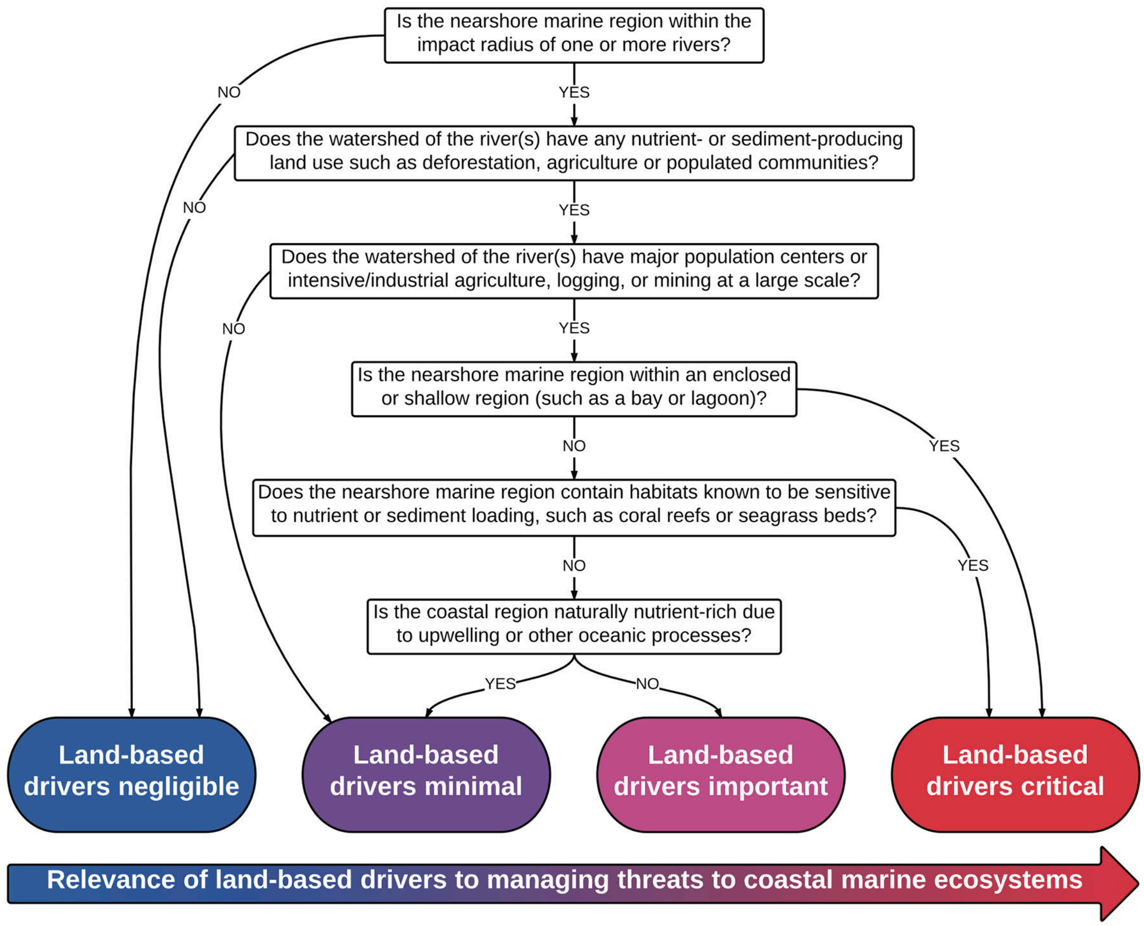

FIGURE 1 | Decision tree to classify coastal marine regions by the relevance of managing human-caused, land-based drivers that produce nutrient, or sediment loading to their conservation. Levels of the decision tree are intended for relative comparison among regions and conservation priorities, not to provide any absolute index of risk. Users of the decision tree should always choose the more conservative path if they are uncertain.

ecology to identify a set of variables that influence whether human activities produce elevated nutrient or sediment loads in a watershed, how that load is transported to the coastal oceans, and how coastal ecosystems respond (Vitousek et al., 1997; Carpenter et al., 1998; Cloern, 2001; Mayorga et al., 2010; Fabricius, 2011; Milliman and Farnsworth, 2011). Second, to reduce the complexity of the decision tree and eliminate redundancy, we removed nested variables to create a superset of traits (e.g., the influence of precipitation on runoff was subsumed into the broader category of volume of river water exported). Third, we eliminated factors that could not be adequately represented in the decision tree, either because those factors did not fit into a bifurcating yes/no framework (such as ecosystem resilience), or because data needs were impractical or expensive (e.g., nutrient concentrations in water). With that final set of simple criteria, we organized the decision tree such that lower levels have no bearing on higher levels—for example, human presence directly affects habitat vulnerability, but habitat vulnerability does not directly affect human presence. To make the decision tree generalizable to data-limited environments, it does not require highly accurate quantitative inputs (Álvarez-Romero et al., 2011). Instead, it relies on expert knowledge from the decision tree users regarding the region of interest, the surrounding area, and the river(s) and watershed(s) affecting it.

The point of reference for the decision tree is intended to be a nearshore marine area. The size of the area is intentionally undefined, because most managers and conservationists will approach this decision tree with a particular management unit, community area, or ecological patch in mind. If the region of interest is extremely small, such as several square meters, the outcome of the decision tree will not be informative from a management standpoint. Conversely, a region of interest that is too large, such as the whole drainage of the Mississippi River, may encompass multiple areas that follow different paths through the decision tree. Research demonstrating the importance of ecosystem connectivity in conservation planning suggests that larger patches may be more appropriate in some cases (Beger et al., 2010; Klein et al., 2010; Álvarez-Romero et al., 2011; Brodie et al., 2012; Makino et al., 2013).

The results of the decision tree describe whether land-based drivers are negligible, minimal, important, or critical for the marine region in question. These labels refer to *human-caused* land-based drivers, recognizing that natural land-based drivers may have profound impacts on the oceans but are unlikely to cause ecological degradation. The terminology is relative and is not an absolute index of risk, nor is it a framework to prioritize management efforts among other human-caused threats, such as overfishing or climate change.

Below we provide justification for the six steps of the decision tree and explain how a user should proceed at each step (**Figure 1**). If users are uncertain how to answer a question in the decision tree, we recommend choosing the most conservative path (i.e., employing the precautionary principle).

River Impact Radius

"Impact radius" refers to the area that falls within a river plume. To understand which marine regions are exposed to runoff, we ask users to qualitatively decide whether the region of interest is affected by a river plume. Recognizing that nutrients and other dissolved matter are transported further than sediments, this level of the decision tree refers to the freshwater plume that contains dissolved nutrients and may encompass a smaller sediment plume. In Northern Chile, for example, only one river (the Loa) reaches the Pacific, so any marine region outside the plume of the Loa is unlikely to be influenced by land-based runoff (Romero et al., 2003). Users of the decision tree may conclude that their region of interest is within the impact radius of a river if it is affected by numerous small rivers, from distinct watersheds with overlapping plumes (Maughan and Brodie, 2009) or if the region is near a freshwater outlet that is not strictly considered a "river," such as a slough (Caffrey et al., 2002); or if the region is not within the impact radius of a perennial river but nonetheless experiences episodic large freshwater pulses from ephemeral rivers (Alexandrov et al., 2003). The Coriolis effect, strong currents, or winds may skew a plume in one direction along the coast or force its impacts further offshore (Gan et al., 2009; Schiller et al., 2011). Therefore, risks from a single plume can be spatially asymmetrical. If users are uncertain whether their region of interest is within the impact radius of any river, they should answer "yes" and proceed to the next level of the tree.

The Presence of Runoff-Producing Land Use in the Watershed(s)

Even if the region of interest is affected by a river plume, if there is little human activity in that river's watershed, the potential for human-caused runoff is negligible. If high nutrient or sediment loading exists in that river, it would be due to natural sources and not a target for management action (Albert et al., 2015). Consequently, those regions fall into the "land-based drivers negligible" category. Note that any type of human land use would merit a "yes" in this level, including land use without habitation (such as logging or mining that occurs in an uninhabited watershed) or human settlements without further land conversion, such as a town that sits on a river in an otherwise intact watershed.

The Presence of Intensive Land Uses in the Watershed(s)

Among regions that do have runoff-producing human activities in the relevant watershed(s), a gradient of land use impacts exist. This level is intended to capture that continuum within the bifurcating structure of the decision tree by separating highly impacted watersheds from minimally impacted ones. Examples of intensive land use include industrial or high-intensity agriculture, mining that displaces large volumes of sediments or soils, widespread deforestation or land conversion, and the building of large cities (Carpenter et al., 1998). A low-intensity human activity that merits a "no" at this level of the decision tree might be a watershed with several hundred people and minimal land conversion (Howley et al., 2013).

Physical Processes along the Coast Near the River Mouth

One critical determinant of nutrient and sediment impact on marine ecosystems is the concentration and residence time of nutrients and sediments once in the coastal zone (Fabricius, 2005; Howarth et al., 2011). Open, well-flushed coastal areas will dissipate river loads relatively quickly, minimizing the impact on marine life from both nutrient loading and sedimentation (Fabricius, 2005). A bay, estuary, or shallow shelf may have relatively little mixing and will retain the river load longer, possibly resulting in greater ecological degradation (Glibert et al., 2011; Brodie and Waterhouse, 2012). Based on a multitude of cases where a heavily used watershed draining into a shallow, partially enclosed region experienced severe degradation from nutrient runoff (Murray and Parslow, 1999; Kemp et al., 2005; Drupp et al., 2011; Lipizer et al., 2011), within this decision tree, we assign all such regions to the highest category of concern. Users of the decision tree should answer "yes" to this question if they believe the region of interest has reduced mixing due to the geographic features of the coastline.

The Presence of Sensitive Marine Habitats

Marine ecosystems differ markedly in their sensitivity to nutrient or sediment loads. Even episodic or low-level sediment loading may cause degradation to coral reefs and seagrass beds (Fabricius, 2005). Low but chronic levels of nutrient loading can also cause ecological damage to coral reefs (Fabricius, 2005) but other ecosystems such as kelp forests are resilient to nutrient loading and may experience enhanced productivity when stimulated by nitrogen runoff (Steneck et al., 2002). This level of the decision tree sorts regions with ecosystems sensitive to nutrient loading, sediment loading, or both into the "land-based drivers critical" category.

Background Levels of Nutrient Richness due to Upwelling

Any region of interest that reaches this last level of the decision tree is within the impact radius of a river that drains a watershed impacted by humans, but has a relatively open coastline and no sensitive habitats. Consequently, sediment loading is not likely to be a major pressure, and this final level addresses only the risk of nutrient loading. We divide regions into the "land-based drivers minimal" and the "land-based drivers important" categories based on whether upwelling or other coastal processes naturally bathe the region in nutrient-rich waters during at least part of the year. Among the regions left in this level, those that both experience rapid mixing due to upwelling, and likely have marine ecosystems that are adapted to a naturally nutrient-rich environment, are considered at less risk and assigned the "land-based drivers minimal" category. While we recognize that even these resilient ecosystems may eventually be degraded by sustained and intense nutrient or sediment loading (Nelson and Zavaleta, 2012), as discussed elsewhere, we did not incorporate ecological thresholds into the decision tree framework.

APPLICATION

We evaluated nearshore marine ecosystems in five regions around the world (**Figure 2**) to ground-truth the decision tree. They are presented below, in order of increasing relevance of land-based drivers to marine conservation. The case studies were chosen to represent both temperate and tropical climates, to be distributed throughout the world, to characterize different paths through the decision tree, and to describe unique local circumstances that influence the ecological impacts of nutrient and sediment loading but are not captured in the general framework of the decision tree.

Rennell, Solomon Islands (11°39′ S, 160°15′ E)

The region of interest is the entire East Rennell World Heritage Area, a raised (200 m) coral reef atoll (Taylor, 1973). Rennell is a limestone island with no significant surface water flows, instead rainfall rapidly infiltrates into groundwater systems; for that reason, the first level of the decision tree assigns it to the "land-based drivers negligible" category. The island is surrounded by a narrow (100 m) shallow lagoon and fringing reef system that drops away quickly into deep (500–1000 m) oceanic waters. The high turnover of these oceanic waters further reduces any impact

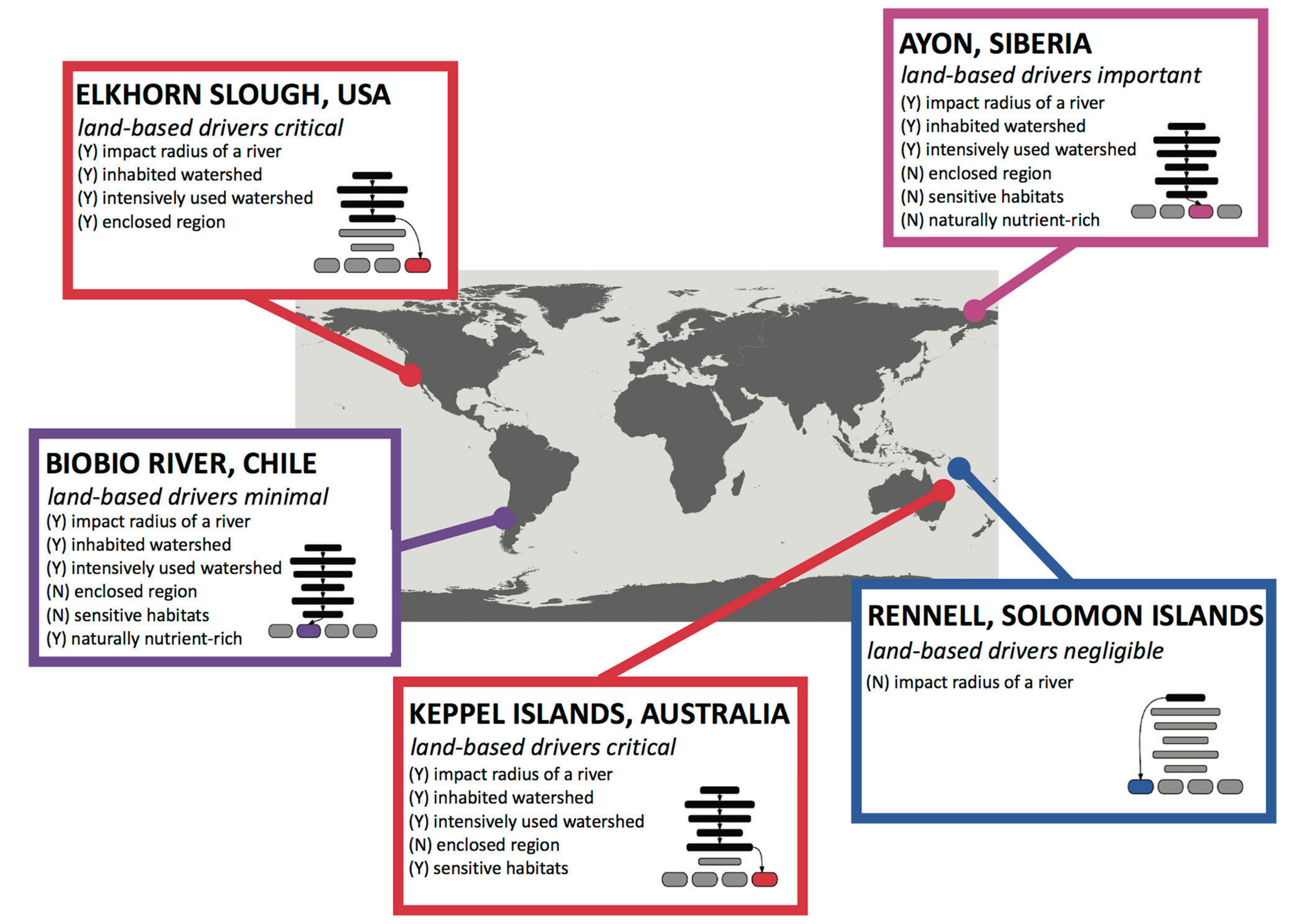

FIGURE 2 | Map of case studies evaluated using the decision tree, and a summary of their classifications. The boxes indicate whether the case study was assigned a "yes" or a "no" at each level of the decision tree, and are color-coordinated to the decision tree result categories. The miniature decision trees represent the path taken through the decision tree for each case study. Map generated using ArcGIS software and basemaps from Esri.

of terrestrial runoff. Even though there are increasing pressures of logging and mining on the terrestrial environment, the coral reefs in Rennell generally remain in very good condition, with limited impact from fishing pressure adjacent to population centers (Albert et al., 2013).

Bíobío River, Chile (36°49′ S, 73°11′ W)

The region of interest in this case study is the coastal ocean just beyond the mouth of the Bíobío River. The second largest river in Chile, the Bíobío, is 380 km long and reaches the Pacific Ocean just past the city of Concepción. The region of interest is within the impact radius of this river, and the Bíobío watershed encompasses a major city (Saldías et al., 2012), so we would answer "yes" for this region in the first three levels of the decision tree. The coastline at the outlet of the Bíobío is straight and not embayed, so this region would proceed through the fourth level of the decision tree. Because no sensitive coastal marine habitats have been recorded near the river mouth (Sellanes et al., 2008), this region would reach the final level of the decision tree. Seasonal upwelling plays a powerful role along this open coastline (Sobarzo et al., 2007), and so this region falls into the "land-based drivers minimal" category.

Ayon, Siberia (69°56′ N, 167°57′ E)

The region of interest is the marine area immediately offshore from Ayon, a tiny settlement on the East Siberian Sea, and was selected as a location typical of much of the Russian Arctic. Although we found little literature on the marine ecology of this region, we include it as an example application of the decision tree to a data-poor region. This region has numerous small rivers, but four enormous Russian rivers (Ob, Yenisei, Lena, and Kolyma) discharge thousands of cubic kilometers of freshwater into the Arctic annually from almost 9 million square kilometers of land (Milliman and Farnsworth, 2011); as such, any location on the Russian Arctic coast is likely affected by at least one river plume. Ayon is ∼250 km away from the outlet of the Kolyma River, which has been dammed for hydroelectric power, and has increased sedimentation from gold mining (Bobrovitskaya et al., 2003; Majhi and Yang, 2008). Although it is unclear how severely impacted the watershed is at this stage, we answer "yes" to the third level of the decision tree to be conservative. Ayon sits on an open coastline with little upwelling (Milliman and Farnsworth, 2011). The marine habitats of the East Siberian Sea are not well-characterized, but we found no evidence of strong nutrient sensitivity in Arctic ecosystems (Piepenburg et al., 2011; Roy et al., 2014), so Ayon falls into the "land-based drivers important" category.

Elkhorn Slough, California (36°48′ N, 121°47′ W)

The region of interest is the small area of Monterey Bay adjacent to Moss Landing, California where Elkhorn Slough empties into the bay. Because Elkhorn Slough is connected via a small channel to the Salinas River, this region is within the impact radius of a river (as defined by this study). Due to intensive agriculture both surrounding Elkhorn Slough and in the connected Salinas River Valley, Elkhorn Slough has some of the highest recorded nutrient loading—and highest variability—of any temperate estuary in the world (Caffrey et al., 2002; Wankel et al., 2009; Hughes et al., 2015). The watershed experiences intensive human impacts, and so it proceeds to the fourth level of the decision tree. Because this region is within a bay, albeit a large, deep, well-mixed one (Rosenfeld et al., 1994), it is placed in the "land-based drivers critical" category by the decision tree. Mitigation of land-based runoff is all the more critical here, because nutrient influx into Elkhorn Slough in the past half-century has been so intense—increasing exponentially over the past 40 years (Hughes et al., 2013)—that the terrestrial and estuarine vegetation's capacity to protect the marine environment may well be compromised and in need of recovery.

Keppel Islands, Great Barrier Reef, Australia (23°07′ S, 150°56′ E)

The Keppel Islands tropical coral reefs are adjacent to and within the impact radius of the Fitzroy River, one of the largest watersheds on the Queensland coast adjacent to the Great Barrier Reef Marine Park. In investigating this region, we answer "yes" to the second and third levels of the decision tree, because modification of the Fitzroy River watershed through the introduction of sheep and cattle, extensive clearing, mining, and intensive agricultural development has resulted in a massive increase in suspended sediment and nutrient runoff (Seabrook et al., 2006; Kroon et al., 2012). The Keppel Island reefs are not situated in a bay or other protected region, but they do contain sensitive habitats, and consequently are classified as "land-based drivers critical." Recent research has demonstrated that increased exposure to sediment and nutrients during flooding events has been a strong driver in coral disease and decline (Lamb et al., 2016; Wenger et al., 2016) indicating that land-based drivers are vital for the survival of Keppel Island reefs.

DISCUSSION

The decision tree presented here provides a simple framework to standardize our understanding of where nutrient and sediment runoff should be included in the scope of marine conservation projects. It is intended to help managers and other conservation stakeholders determine whether nutrient and sediment loading could be a concern in protecting coastal regions, before embarking on costly and challenging land-sea planning initiatives. Even if a manager is sufficiently familiar with runoff processes and the local context that the results of the decision tree are unsurprising, the decision tree enables managers to formalize this knowledge in a way that may improve communication and confidence in planning decisions. As demonstrated in the case studies, this decision tree provides a systematic foundation for considering the relevance of land-based drivers to marine conservation, and generally agrees with published literature where it is available. The decision tree is not intended to replace any regional planning process, but rather to enhance and standardize assessments of whether embarking upon land-sea management is necessary to protect marine ecosystems. This decision tree helps to align perspectives on how problematic runoff is in different regions, and strikes a balance between detail and generalization.

Advances in integrated land-sea planning have provided numerous tools for managers to effectively and efficiently address land-based impacts when they threaten coastal and marine ecosystems (Klein et al., 2010; Álvarez-Romero et al., 2011; Makino et al., 2013). However, land-sea planning is inherently difficult and complex, and its incorrect application might have problematic consequences for managers. Undertaking a land-sea planning initiative in a region where runoff is not a major threat could divert resources from more critical conservation initiatives. As concerns grow worldwide among governments and conservation organizations regarding the harm runoff poses to coastal oceans, the likelihood of managers failing to prioritize conservation actions and focusing on runoff instead of more pressing threats could also increase. Conversely, failing to incorporate land-sea planning in regions where the coastal marine environment is profoundly influenced by anthropogenic nutrient and sediment loading may lead to ecological degradation. Some declines in coastal water quality due to terrestrial human activities far predate modern marine management (Rabalais et al., 2002), and others have occurred or worsened in recent decades, despite management plans intended to protect coastal oceans (Brodie and Waterhouse, 2012). Many current marine management endeavors still omit consideration of runoff entirely, due to a lack of data or a focus on fishing and other oceanic threats. For example, a recent National Marine Conservation Assessment for Papua New Guinea did not incorporate nutrient and sediment loading due to a lack of data on runoff and its impacts, despite recognizing runoff as a "key threat" (Government of Papua New Guinea, 2015). This decision tree should enable managers to consider runoff without investing precious time and resources in a formal land-sea planning process unless it is truly necessary in their system.

A broad array of rapid assessment tools such as this decision tree, and synthesis tools that use global data instead of local inputs, have become widespread in natural resource management in recent decades (Stem et al., 2005). Because the application of these tools is rarely replicated, and conservation outcomes are rarely monitored for the influence of these tools, it is often challenging to establish their true efficacy or impact (although see Halpern et al., 2015). Some of these tools are quantitative and pre-packaged for widespread use, but still require some local data inputs, such as the Integrated Valuation of Ecosystem Services and Tradeoffs model (Nelson et al., 2009). As mentioned previously, other qualitative tools have been developed to explore management options for "cross-system" threats such as human-caused terrestrial runoff to the coastal oceans (Álvarez-Romero et al., 2011, 2015). To our knowledge, this decision tree is the first tool to provide guidance on whether or not to consider land-sea planning at all.

This work addresses both nutrient and sediment loading; however, these pressures differ both in their spatial and temporal dynamics. The response of coastal ecosystems to dissolved nutrients is likely affected by the temporal dynamics of nutrient transport, and the nutrient composition of runoff relative to the oceans (Paerl et al., 2014), which we did not include in order to preserve the simplicity and utility of the decision tree. Nutrient loading may affect a broader marine area because it is transported further than sediment in freshwater plumes (Maughan and Brodie, 2009). Sediments typically remain more concentrated around the river outlet than nutrients, and have longer-lasting ecological impacts than nutrients, both because nutrients can be rapidly removed by biological processes and because sediment can be re-suspended (Risk, 2014). Sedimentation may also cause ecological degradation from just one or a few episodic pulses (Risk, 2014), while nutrient loading is more likely to be problematic at chronic levels (Lapointe et al., 2004a). Sediment has a complex role at the land-sea interface that we did not fully capture in the decision tree: humans both increase (via land conversion) and decrease (via dams) sediment loads in rivers (Syvitski et al., 2005), and coastal ecosystems may benefit (e.g., Mississippi River Delta; Blum and Roberts, 2009) or suffer (e.g., coral reefs; Fabricius, 2005) from sedimentation.

Although we primarily discuss its applications to nutrient and sediment loading, this framework could be expanded to address other pollutants transported by rivers to coastal oceans. Sediment, nutrient, and chemical pollution tend to occur together, downstream of agriculture, logging, landfill, and mines (Peters et al., 1997), but data and insight regarding the production and transport of chemicals through the land-sea interface is very limited relative to our knowledge of nutrients and sediments (Maughan and Brodie, 2009). Unlike nutrients and sediments, chemicals may be transported to coastal and marine ecosystems via multiple pathways other than watersheds (e.g., oil spills, sewage outfalls), and their effects depend not only on their concentrations but also on their type (e.g., heavy metals, oils, pesticides, and herbicides; Peters et al., 1997). We hope that in the future, the ecotoxicology literature will provide sufficient research on coastal and marine ecosystems to enable the inclusion of chemical pollution in this decision tree framework.

The decision tree should be used with the current state of affairs in mind. However, we acknowledge that the temporal dimension is crucial for conservation. Historic degradation of watersheds and coastal marine habitats may have consequences for decades, even if the activity that generated the original damage no longer occurs (Kemp et al., 2005). The decision tree also does not incorporate the risk of future human activities. In regions where managers might anticipate damaging human activities increasing in the future, proactive land-sea planning might avoid deleterious impacts entirely. Protection of coastal and marine ecosystems is typically less costly and more effective than restoration; therefore, we strongly encourage any managers expecting increased anthropogenic impacts in the future to consider land-sea planning now.

Identifying the influence of land-based drivers on coastal and marine ecosystems is only the first step in effective management. If land-based drivers are found to negatively impact a nearshore marine region, what should managers do? First, all marine managers can acknowledge the effects of runoff—however great or small—on their regions. Taking a cumulative impacts approach to ecological health, as opposed to focusing on individual threats, frequently worsens the outlook for coastal oceans, and highlights the importance of protecting ecosystems before combined human activities push them over critical thresholds (Halpern et al., 2007, 2008b). Considering the possible deleterious impacts of nutrient or sediment loading, in addition to other more frequently recognized threats such as fishing, may change management priorities, and cost-effectiveness of interventions (Halpern et al., 2008a; Klein et al., 2010). For example, declining water quality may undermine the success of marine protected areas whose locations were chosen based primarily on fishing effort or habitat protection (Boersma and Parrish, 1999). Second, managers may consider attempting to actively mitigate the runoff threat. Because most marine managers do not have direct jurisdiction or much influence over terrestrial activities that generate runoff, any mitigation of nutrient or sediment loading may have to be preceded by inter-agency cooperation and the possible involvement of higher authorities. Mitigation options include limiting or strategically shifting the nutrient- or sediment-producing activity (or buying out the industry or property); protecting riparian zones, wetlands, and other coastal buffers that filter nutrients and sediments from freshwater; and investing in improved urban wastewater management (Mitsch et al., 2001). In coastal regions and islands with traditional stewardship systems, oversight of different activities and sections of the land-sea continuum may be much more tightly linked, and managing runoff may be simpler as a result. In all of these cases, a formal land-sea planning process will help managers identify which activities are most feasible and cost-effective in their regions (Klein et al., 2010; Álvarez-Romero et al., 2011; Makino et al., 2013).

The decision tree is intentionally based on purely environmental factors, and only addresses the relevance of land-based nutrient and sediment loading to nearshore marine ecosystems. The results of the decision tree, and the management options outlined above, must be considered in light of the local social and economic context. In Appendix S1, we outline a non-exhaustive list of social and economic considerations that are important to land-sea management but are not captured in our purely environmental decision tree. These considerations include culture and politics, revenue and livelihoods, health and nutrition, ecosystem services, and the watershed context. We stress, however, that the first step in addressing land-based pressures from the marine perspective should be to methodically determine whether they matter for the health of coastal oceans.

CONCLUSION

The research presented contributes to a more systematic and holistic approach to studying and understanding coastal runoff. We suggest that the importance of considering land-based impacts for conservation can be identified using a simple decision tree, which has minimal data requirements. In some regions the impacts of actions on land may be negligible relative to other concerns. Systematic consideration of the vulnerability of coastal ecosystems to land-based impacts will help regional and federal conservation managers to avoid wasted efforts in less vulnerable regions, and to focus their efforts in higher risk areas. Even in regions where managers are very familiar with the runoff context, the decision tree can be used to justify and standardize the choice to invest in land-sea planning or not. Ultimately, this will result in more timely and effective conservation actions.

AUTHOR CONTRIBUTIONS

This research was conceived by the entire group of authors at a meeting of the SNAPP Ridges to Reef Fisheries working group. AFH constructed the decision tree with substantial input from BH and SG. AFH also drafted the paper with substantial input from all authors. Additionally, CB and SA provided expertise on plume dynamics and sediment transport; CK, SM, and LT provided conservation planning and management perspective; and JN, SA, and AW contributed case studies to the paper.

ACKNOWLEDGMENTS

This research was conducted by the Ridges to Reef Fisheries Working Group supported in part by SNAPP: Science for Nature and People Partnership, a collaboration of The Nature Conservancy, the Wildlife Conservation Society and the National Center for Ecological Analysis and Synthesis (NCEAS). AFH was supported by the Department of Defense (DoD) through the National Defense Science and Engineering Graduate Fellowship (NDSEG) Program. AFH gratefully acknowledges Patricia Faundez for helping with the Bíobío River case study. JN thanks the NatureNet Science Fellows program of the Nature Conservancy and Stanford University.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fmars.2016.00273/full#supplementary-material

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.